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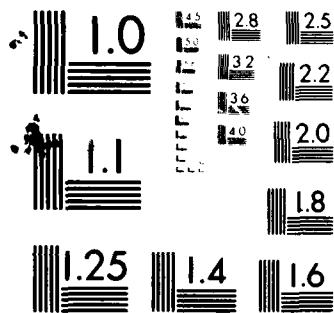
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NAVAL ENVIRONMENTAL PREDICTION RESEARCH FACILITY
CONTRACTOR REPORT
CR 81-85

AD A108756

ATLANTIC HURRICANE WIND PROBABILITY FORECASTING (WINDPA)

Prepared By:

Jerry D. Jarrell

Science Applications, Inc.
Monterey, CA 93940

Contract No. N00228-80-C-GA08

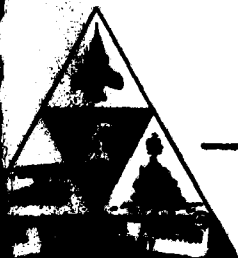
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NAVENVPREDRSCHFAC Contractor Report CR 81-05	2. GOVT ACCESSION NO. AD-A108 756	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Atlantic Hurricane Wind Probability Forecasting (WINDPA)	5. TYPE OF REPORT & PERIOD COVERED Final	
7. AUTHOR(s) Jerry D. Jarrell	6. PERFORMING ORG. REPORT NUMBER	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Science Applications, Inc. (SAI) 2999 Monterey-Salinas Highway Monterey, CA 93940	8. CONTRACT OR GRANT NUMBER(s) N00228-80-C-GA08	
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Systems Command Department of the Navy Washington, DC 20361	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS PE 63207N PN 7W0513 NEPRF WU 6.3-14	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Naval Environmental Prediction Research Facility Monterey, CA 93940	12. REPORT DATE October 1981	
	13. NUMBER OF PAGES 22	
	15. SECURITY CLASS. (of this report) UNCLASSIFIED	
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Wind probability Tropical cyclone Hurricane		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The Atlantic Hurricane Wind Probability (WINDPA) program is documented. WINDPA, which is operated at Fleet Numerical Oceanography Center, Monterey, CA, provides the probability of selected Navy and Air Force bases either being struck by an Atlantic Ocean tropical cyclone or receiving winds of at least 30 or 50 kt. The basis for WINDPA estimates is discussed in comparison to a similar western Pacific program (WINDP). WINDPA estimates were subjected to independent reliability testing, the results of which are discussed.		

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1.0 Introduction

The Atlantic Hurricane Wind Probability (WINDPA) model is a continuation of the Atlantic Hurricane Strike Probability Program developed by Jarrell¹ (1981). This model extends the Atlantic strike probability model using wind probability concepts similar to those developed and presented for the western Pacific Ocean basin (Jarrell², 1981). Those concepts will not be presented again here except to illustrate the differences in methodology between the two models. The parameterization of the asymmetric wind distribution around the tropical cyclone and the inference of 30 and 50 knot wind radii are different and will be described.

2.0 Model Description

2.1 Atlantic Hurricane Strike Probability Program

The strike probability concept was developed by Jarrell³ (1978) and has been successfully applied to the eastern and

¹Jarrell, J.D., 1981: Atlantic Hurricane Strike Probability Program; NAVENVPREDRSCHFAC Contractor Report CR81-04.

²Jarrell, J.D., 1981: Tropical Cyclone Wind Probability Forecasting (WINDP); NAVENVPREDRSCHFAC Contractor Report CR81-03.

³Jarrell, J.D., 1978: Tropical Cyclone Strike Probability Forecasting; NAVENVPREDRSCHFAC Contractor Report CR78-01.

western Pacific as well as the Atlantic basin. The development of strike probability theory and its extension to wind probability is based upon three basic assumptions:

- (a) All forecasts related to tropical cyclones are subject to some degree of error.
- (b) The size of the position forecast error is statistically related to the relative difficulty of the forecast.
- (c) The occurrence of position forecast errors is random and approximates a bivariate normal probability distribution ; normal in both N-S and E-W directions.

Investigators verified these assumptions in each basin in separate studies; Nicklin⁴(1977) in the western Pacific, Thompson and Elsberry⁵(1979) in the eastern Pacific and Crutcher⁶(1980) in the Atlantic. In these studies statistical

⁴Nicklin, D.S., 1977: A Statistical Analysis of Western Pacific Tropical Cyclone Forecast Errors; Naval Postgraduate School; M.S. Thesis.

⁵Thompson, W.J. and R.L. Elsberry, 1979: A Statistical Analysis of Eastern Pacific Tropical Cyclone Forecast Errors; 12th Tech. Conf. on Hurricanes and Tropical Meteorology; New Orleans; April, 1979.

⁶Crutcher, H.L., 1980: Tropical Storm Forecast Error and the Bivariate Normal Distribution. 13th Tech. Conf. on Hurricanes and Tropical Meteorology; AMS; Miami, FL; Dec, 1980.

methods were used to group the forecasts into three classes of relative forecast difficulty of easy, average and difficult. The resultant classifications yielded respective relative forecast error groups of below average errors (Class I), average errors (Class II) and larger than average errors (Class III). Statistical parameters were developed in each study to describe the bivariate normal distributions for each of these three classes and for 24, 48 and 72 hour forecasts. Although relative separation of groups varied in the three studies, three distinct groups emerged in each.

The statistical data provided the basis for a strike probability model for the respective basins. Using forecast positions and integrating in time and space, probabilities of a tropical cyclone strike are derived for forecasts out to 72 hours.

Crutcher (1980) used a clustering model (NORMIX) to develop three discrete bivariate normal populations of Atlantic position forecast errors. Because uncertainty is involved in categorizing a particular forecast as a member of a single forecast difficulty class (even after-the-fact it is a probabilistic problem), a method (Jarrell¹, 1981) was developed to assign "probability of class membership" to each forecast. A series of stepwise linear regression equations were fit to predictors relating class probabilities to the predictors. A forecast would have a likelihood of belonging to Class I, II or III and possessing those populations characteristics. Each of

these predicted probabilities is constrained to $0 \leq P_x \leq 1$ and that $P_1 + P_2 + P_3 = 1$. The actual strike probability then is derived from three separate runs; each run using the bivariate parameters from a different population. The final probabilities are a sum weighted by the predicted class probabilities. This method also forms the basis of the Atlantic wind probability model class selection.

2.2 Western Pacific Wind Probability Model (WINDP)

The wind probability model enhances the strike model by providing probabilities of sustained winds of 30 and 50 knots at a user specified site. A definite advantage is realized for the user in that he can relate probabilities to a recognized destructive wind force (i.e., 30 or 50 knots) rather than to an arbitrarily selected distance which constitutes a tropical cyclone strike. The WINDP model is based on the strike model plus an evaluation of maximum wind and wind radius forecasts. This evaluation is based on the Riehl⁷ (1963) profile $VR^{1/2} = \text{constant}$, or $R_c = (V_m/V_c)^2 R_m$, where R_c , V_c are a radius and wind speed of concern and V_m , R_m are a maximum wind speed and associated radius. Using forecast warning data to obtain V_m and inferring R_m from the radius of 50 or 30 knot winds, R_c can then be approximated.

⁷Riehl, H., 1963: Some Relations Between Wind and Thermal Structure of Steady State Hurricanes; Journal of Atmospheric Science; Vol. 20; July, 1963, pp 276-287.

R_m and V_m are treated as random variables. They are forecast values and are assumed to be related. All values of V_m are considered and its probability of occurrence estimated from a wind error algorithm. For each such V_m , an expected value of R_m is predicted and from $Vr^{1/2} = \text{constant}$, a value of R_c is computed. The marginal probability of the point of interest receiving winds $\geq V_c$ (given the currently assigned V_m value) is the probability that the cyclone passes within distance R_c of the point. The total probability that a point will receive winds of at least V_c at a time step is then estimated by summing over all V_m values.

Asymmetry of tropical cyclone storm pattern (i.e., a larger semicircle for equal isotach winds to the right of storm track) is treated as a series of circular isotachs offset to the right of the forecast track. The forward speed of motion (S) of a storm is added to a stationary storm maximum wind (V_s) to approximate the maximum wind in right semicircle ($V_m = V_s + S$), and subtracted ($V_s - S$) to approximate the left semicircle. An offset distance is then calculated by substituting into the Riehl equation and simplifying to obtain:

$$D = (2S(V_m - S)/V_c^2)R_m ,$$

where $V_m = V_s + S$. The offset is then applied to the left of the point of concern (to compensate for larger storm semicircle on right side of storm) and used to determine a center for integration. Both wind profile derivation and asymmetric offset are fully developed by Jarrell²(1981) for the interested reader.

2.3 Atlantic Wind Probability Model

The basic differences to be observed in the Atlantic model as compared to the western Pacific are minor in nature and lie in the derivation of the 50 and 30 knot wind profiles and the method in which asymmetry is handled.

The basis for derivation of the wind profiles is from work by Tsui⁸(1980). Tsui extracted wind radius data from tropical cyclone warnings issued by the Joint Typhoon Warning Center on Guam for a 12-year period (1966 to 1977). From this data set he estimated the profile of the tangential wind speed along the radial axis to be exponential. The study also indicated that the size of a tropical cyclone is statistically related to maximum wind and persistence and that the asymmetric shape of the isotach is correlated to the speed of movement.

The asymmetric shape of the wind distribution was parameterized by expressing all directional radii as fractions of the radius on the right side. For example the average fraction of the left side of the 50-knot wind radius is 0.73 and the 30-knot wind radius is 0.81. This asymmetry is related to speed of storm movement and is more pronounced at higher speeds.

⁸Tsui, T.L., 1980: Surface Wind Distribution of Western North Pacific Tropical Cyclones; 13th Tech. Conf. on Hurricanes and Tropical Meteorology; Miami, FL; Dec, 1980.

By scaling of both the wind and the right side wind radius, data was then composited and fitted to a single profile,

$$V/V_{\max} = \exp(-0.693R) ,$$

where V is the wind speed of interest, V_{\max} is the maximum wind (intensity) and R is the ratio of the radius associated with V to the radius associated with winds of one half V_{\max} in a tropical cyclone.

The advantage of the Tsui profile over the Riehl profile for this purpose relates to the scaling radius used. Riehl uses the radius of maximum winds (R_m) as his scaling radius. R_m is small (on the order of 20-30 miles) and is subject to very large percentage errors. Tsui, on the other hand, uses the radius of 50% of the maximum wind (R_{half}) as his scaling radius. R_{half} is larger (typically 50-150 miles) and is also far enough removed from the central core of winds to be identifiable in synoptic ship reports. For both of these reasons, R_{half} is subject to smaller percentage errors than R_m . Since in both cases the scaling radius is used in ratio to some other isotach radius, percentage error is the relevant measure of accuracy.

With the above relationship plus knowledge of the maximum wind and its radius and one observed wind, an estimate of the wind field around a tropical cyclone can be deduced. Thus with Tsui's wind profile any wind radii may be estimated and storm asymmetry handled with a simple empirical relationship.

3.0 Testing the Atlantic Wind Probability Program (WINDPA)

The methodology used in testing WINDPA predicted values against observed values is identical to that used in the western Pacific by Jarrell²(1981). An array of 30 points in the Atlantic and Gulf of Mexico was selected (figure 1). WINDPA values for 30 and 50 knots were calculated at 12 hour intervals from the effective synoptic time of the National Hurricane Center (NHC) forecasts for the 1980 season. Since most of these 30 points are not observing stations, actual verifying winds were not generally available. Consequently a verifying "warning time" probability greater than 50% constituted a verifying strike.

Tables 1, 2, 3 and 4 compare the expected to the observed occurrences of 30 and 50 knot winds. Predictions are associated with percentage groups of increasing width, $< 1/2\%$, $1/2$ to $1\ 1/2\%$, . . . etc. Time integrated probabilities were verified only if a continuous record was available over the entire time period.

50 KT

A<P<B	24 Hr			48 Hr			72 Hr		
	N	E	O	N	E	O	N	E	O
< ½%	5684	0	0	3661	0	0	2691	0	0
½- 1½	39	0	0	115	1	0	216	2	2
1½- 3½	30	1	0	81	2	2	108	2	4
3½- 7½	27	1	1	39	2	4	15	1	2
7½-15½	23	2	2	4	0	2*	0	0	0
15½-31½	14	3	4	0	0	0	0	0	0
31½-63½	3	1	1	0	0	0	0	0	0
>63½	0	0	0	0	0	0	0	0	0
ALL	5820	9	8	3900	5	8	3030	5	8

Table 1. Instantaneous Probabilities.
50 kt winds - Expected versus Observed.

30 KT

A<P<B	24 Hr			48 Hr			72 Hr		
	N	E	O	N	E	O	N	E	O
< ½%	5576	1	1	3550	0	0	2520	1	1
½- 1½	65	1	1	109	1	1	195	2	0
1½- 3½	50	1	1	94	2	1	178	4	4
3½- 7½	34	2	1	85	4	5	136	6	14*
7½-15½	29	3	3	61	7	14*	1	0	0
15½-31½	35	8	8	1	0	1	0	0	0
31½-63½	31	14	14	0	0	0	0	0	0
>63½	0	0	0	0	0	0	0	0	0
ALL	5820	29	29	3900	14	21	3030	13	19

Table 2. Instantaneous Probabilities.
30 kt winds - Expected versus Observed.

*difference significant at 5% level. (None of these are significant when it is assumed that only 1/3 of cases are independent.)

50 KTS

A<P<B	24 Hr			48 Hr			72 Hr		
	N	E	O	N	E	O	N	E	O
< ½%	4980	0	0	2651	0	0	1409	0	0
½- 1½	50	0	0	92	1	0	98	1	0
1½- 3½	22	1	0	75	2	0	92	2	0
3½- 7½	18	1	0	70	4	0	100	5	0*
7½-15½	33	4	1	51	6	2	102	11	4*
15½-31½	19	4	2	29	6	.9	37	8	14*
31½-63½	27	13	11	22	10	11	13	6	6
>63½	11	8	7	10	8	6	9	7	5
ALL	5160	31	21	3000	37	28	1860	40	29

Table 3. Time Integrated Probabilities.
50 kt winds - Expected versus Observed.

30 KT

A<P<B	24 Hr			48 Hr			72 Hr		
	N	E	O	N	E	O	N	E	O
< ½%	4836	0	0	2562	0	0	1322	0	0
½- 1½	61	1	0	85	1	0	93	1	0
1½- 3½	47	1	1	71	2	0	91	2	0
3½- 7½	42	2	1	73	4	0	95	5	0*
7½-15½	36	4	2	92	10	3*	136	16	6*
15½-31½	50	12	8	57	12	12	77	16	19
31½-63½	47	22	17	34	15	20	29	12	19*
>63½	41	33	28*	26	22	20	19	14	12
ALL	5160	74	57*	3000	65	55	1860	66	56

Table 4. Time Integrated Probabilities.
30 kt winds - Expected versus Observed.

*difference significant at 5% level. (None of these are significant when it is assumed that only 1/3 of cases are independent.)

STRIKE									
TIME INTEGRATED									
A<P<B	24 Hr			48 Hr			72 Hr		
	N	E	O	N	E	O	N	E	O
< ½%	5019	0	0	2696	0	0	1448	0	0
½- 1½	32	0	0	84	1	0	101	1	0
1½- 3½	20	0	0	76	2	0	86	2	0
3½- 7½	23	1	0	57	3	1	111	6	0*
7½-15½	18	2	1	46	5	3	80	9	5
15½-31½	25	6	5	25	5	4	25	5	7
31½-63½	16	7	4	12	5	5	6	2	2
>63½	7	5	5	4	3	3	3	3	3
ALL	5160	23	15	3000	24	16	1860	28	17*

Table 5. Time Integrated STRIKPA.

INST A<P<B	24 Hr			48 Hr			72 Hr		
	N	E	O	N	E	O	N	E	O
< ½%	5707	0	0	3684	0	0	2727	1	1
½- 1½	35	0	0	120	1	0	242	2	2
1½- 3½	22	1	0	77	2	3	71	1	2
3½- 7½	21	1	0	19	1	1	0	0	0
7½-15½	17	2	2	0	0	0	0	0	0
15½-31½	18	4	3	0	0	0	0	0	0
31½-63½	0	0	0	0	0	0	0	0	0
>63½	0	0	0	0	0	0	0	0	0
ALL	5820	8	5	3900	4	4	3030	4	5

Table 6. Instantaneous STRIKPA.

*difference significant at 5% level. (None of these are significant when it is assumed that only 1/3 of cases are independent.)

Significance of the differences between the expected and the observed, as discussed in previous reports (Jarrell², 1981), is difficult to assess, but using previously developed tests, agreement appears to be very good. The instantaneous probabilities show excellent correlation at all forecast lengths with minor underforecasting at the longer forecast times (48 and 72 hr). The time integrated probabilities displayed a slight tendency toward overforecasting for both 50 kt and 30 kt winds. This was not at a significant level (see note accompanying tables) and the overall results are considered statistically sound. An instantaneous and a time integrated strike probability (STRIKPA) was run on the same data base (Table 5 and 6) and showed comparable agreement between predicted and observed occurrences.

4.0 Operational Products

The Atlantic wind probability program will be available for the preselected points receiving the Atlantic strike program. (The STRIKPA program is actually integrated into the WINDPA program). Probabilities will be given in two modes, instantaneous and time integrated, and at 0, 12, 24, 36, 48, 60 and 72 hours after the warning time. The instantaneous probability will be the probability at the stated time (i.e., 12 hr) and the time integrated will be summed for the 0 to X hour time interval for an estimate of the probability that the event will be observed within that period of time.

The greatest source of probable error for the WINDPA program will be erroneous input data. An internal check for unusual motion (expected to occur only 5% of the time in nature) will be made and suspect motion flagged. The user should then recheck input data for accuracy.

When the forecast track approaches land mass the forecaster should be aware of program bias. This should be minor for seaward approach to low coastal areas or over smaller islands. However, in other cases land influences will appear as rapid decreases in the instantaneous wind probabilities (especially 50 kt winds) near forecast landfall time. This will bias probabilities - overstate them for inland sites and understate them for coastal sites. Time integrated probabilities will be less biased. This problem is caused by wind forecasts being influenced by track forecasts where landfall is concerned. A bad track forecast may cause a bad wind forecast. This was not accounted for either in development nor testing; hence the test results simulate expected actual operational results and some of the minor disparities between expected and observed occurrences no doubt stems from this problem.

SUMMARY

The wind probability model for the Atlantic is largely based on the strike probability program for the Atlantic and the wind probability program for the western Pacific - both currently operational. The single important improvement represented in the concept is the addition of the Tsui wind profile. Test results of the Atlantic WINDPA program demonstrated excellent agreement between expected and observed results.

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